

THE PROPERTIES OF DYNAMICALLY EJECTED RUNAWAY AND HYPER-RUNAWAY STARS

HAGAI B. PERETS^{1,2} AND LADISLAV ŠUBR³

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA, USA 02138

²Technion - Israel Institute of Technology, Haifa, Israel

³Astronomical institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 18000 Praha, Czech Republic
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Abstract

Runaway stars are stars observed to have large peculiar velocities. Two mechanisms are thought to contribute to the ejection of runaway stars, both involve binarity (or higher multiplicity). In the binary supernova scenario a runaway star receives its velocity when its binary massive companion explodes as a supernova (SN). In the alternative dynamical ejection scenario, runaway stars are formed through gravitational interactions between stars and binaries in dense, compact clusters or cluster cores. Here we study the ejection scenario. We make use of extensive N-body simulations of massive clusters, as well as analytic arguments, in order to characterize the expected ejection velocity distribution of runaway stars. We find the ejection velocity distribution of the fastest runaways ($v \gtrsim 80 \text{ km s}^{-1}$) depends on the binary distribution in the cluster, consistent with our analytic toy model, whereas the distribution of lower velocity runaways appears independent of the binaries properties. For a realistic log constant distribution of binary separations, we find the velocity distribution to follow a simple power law; $\Gamma(v) \propto v^{-8/3}$ for the high velocity runaways and $v^{-3/2}$ for the low velocity ones. We calculate the total expected ejection rates of runaway stars from our simulated massive clusters and explore their mass function and their binarity. The mass function of runaway stars is biased towards high masses, and depends strongly on their velocity. The binarity of runaways is a decreasing function of their ejection velocity, with no binaries expected to be ejected with $v > 150 \text{ km s}^{-1}$. We also find that hyper-runaways with velocities of hundreds of km s^{-1} can be dynamically ejected from stellar clusters, but only at very low rates, which cannot account for a significant fraction of the observed population of hyper-velocity stars in the Galactic halo.

1. INTRODUCTION

Runaway stars are those stars observed to have large peculiar velocities ($40 \leq v_{\text{pec}} \leq 200 \text{ km s}^{-1}$ (Blaauw 1961; Gies 1987; Hoogerwerf et al. 2001) and even higher (Martin 2006); the specific definitions vary). A considerable fraction of the early O and B stars population are known to be runaway stars ($\sim 30 - 40\%$ of the O stars and $5 - 10\%$ of the B stars; Stone 1991 and refs. therein). The velocity dispersion of the population of runaway stars is much larger than that of the ‘normal’ early-type stars (Stone 1991). Besides their relatively high velocities, runaway stars are also distinguished from the normal early-type stars by their much lower ($< 10\%$) multiplicity compared with the binary fraction of normal early-type OB stars ($> 50\%$ and up to 100% ; Garmany et al. 1980; Mason et al. 1998; Kobulnicky & Fryer 2006; Kouwenhoven et al. 2007).

Two mechanisms are thought to contribute to the acceleration of regular runaway stars, both involve binarity (or higher multiplicity). In the binary supernova scenario (BSS; Blaauw 1961) a runaway star receives its velocity when the primary component of a massive binary system explodes as a supernova (SN). When the SN shell passes the secondary the gravitational attraction of the primary reduces considerably, and the secondary starts to move through space with a velocity comparable to its original orbital velocity. In the dynamical ejection scenario (DES; Poveda et al. 1967) runaway stars are formed through gravitational interactions between stars in dense, compact clusters. Simulations show that such encounters may produce runaways with velocities up to 200 km s^{-1} , and even higher in more rare cases (Mikkola 1983; Leonard & Duncan 1990; Leonard 1991; Gualandris et al. 2004). These scenarios suggest that

many of the early OB stars formed in young clusters could be ejected from their birth place and leave the cluster at high velocity. Interestingly, observations show that even very massive O-stars could be accelerated to become runaways (Comerón & Pasquali 2007).

In recent years, stars with extremely high peculiar velocities (hyper-velocity stars; HVSs) of a few $\times 10^2 \text{ km s}^{-1}$ have been observed in the Galactic halo (Brown et al. 2005, 2006a,b, 2007; Edelmann et al. 2005). HVSs are thought to be ejected from the Galactic center following a dynamical interaction with the massive black hole (MBH) known to exist in the center (Hills 1988; Hansen & Milosavljević 2003; Yu & Tremaine 2003; Perets et al. 2007; Perets 2009a). Nevertheless, it was suggested that the BSS and/or the DES could eject, under some conditions, stars with extreme velocities (termed hyper-runaways), comparable with those of observed HVSs, possibly explaining the origin of some of these HVSs (Gvaramadze et al. 2009).

Several studies have explored the DES (see Hoogerwerf et al. 2000) using N-body simulations. Most of these have focused on single encounters between a single/binary star and another binary star, and found the velocities of the ejected stars in such encounters (e.g. Gvaramadze et al. 2009). Leonard & Duncan (1990, 1988) explored the dynamical properties of runaway stars and their distribution in a stellar cluster environment, and not in single encounters. Their studies, however, were limited to a relatively small number of simulation of very small clusters (~ 30 stars; in addition to some hybrid N-body - Monte-Carlo simulations of larger clusters of a few hundreds of stars), and hence to very small sample of ejected runaway stars. Recently, Fujii & Portegies Zwart (2011) studied the ejection of stars from large clusters, however, they considered

only dynamically formed binaries, and did not include primordial binaries in their simulations. They also run only a limited number of simulations, which do not provide enough statistics of the high velocity tail distribution of runaways.

Here we develop an analytic understanding of velocity distribution of the fastest runways in the DES. We compare it with a large sample of simulated runaway stars produced in extensive N-body simulations of hundreds of large stellar clusters. These provide us, for the first time, large enough database of runaway stars with high velocities, which could be analyzed statistically. Using our N-body simulations we characterize the ejection rates, velocity distribution, and binarity of dynamically ejected runaway stars. We find cases of stars dynamically ejected at extreme ejection velocities of a few hundreds of km s^{-1} , however these are relatively rare cases and are not likely to explain the vast majority of hyper-velocity stars observed and inferred to exist in the Galactic halo.

2. ANALYTICAL ESTIMATES

We begin by exploring analytically the dynamical ejection scenario for runaway and hyper-runaway stars. We consider an interaction of a binary of mass $M_B = M_1 + M_2$ and a single star M_* . Large accelerations of the single star are assumed to occur when it passes one of the binary components within the semi-major axis, a , of the binary. Assuming that the scattering is dominated by the gravitational focusing, the cross section of the interaction is

$$\sigma(a) \approx \frac{2\pi G M_B a}{v_c^2}, \quad (1)$$

where v_c is the characteristic stellar velocity in the cluster.

The energy exchange between a hard binary and star is comparable to the binary orbital energy. Hence, the energy transfer to the star is of the order

$$\Delta E_* \approx \frac{G M_B M_*}{a}. \quad (2)$$

and the star acquires a large velocity kick, v_{kick} of the order of the orbital velocity of the binary. We are interested in the cases where ΔE_* is much larger than the star's energy before the interaction. The velocity of the ejected star $v_{\text{kick}} \simeq \sqrt{\Delta E}$ is therefore estimated as

$$v_{\text{esc}} \approx \left(\frac{2G M_B}{a} \right)^{-\alpha}, \quad (3)$$

with $\alpha = 1/2$. Simulations of binary-single star encounters suggests a somewhat steeper slope of $\alpha \sim 3/5$ (see figure 4 in Gvaramadze et al. 2009).

The differential cross section per unit volume of the binary-single star interaction with semi-major axis in the interval $\langle a, a + \delta a \rangle$ is

$$\frac{dR(a)}{da} \approx n(a) N_B n_* \sigma(a) v_c \quad (4)$$

where n_B is the number of binaries per unit volume, n_* is number density of stars and $n(a)$ is the differential distribution of semi-major axis of the binaries, which is normalized to unity:

$$\int_{a_{\min}}^{a_{\max}} da n(a) = 1. \quad (5)$$

Let us consider a log constant distribution of the binaries semi-major axis (so called Öpik's law, with $n(a) \propto a^{-\beta}$; $\beta = 1$), representing an empirical distribution of massive binaries (e.g. Kobulnicky & Fryer 2006) and, for testing purposes, an uniform distribution $n(a) = \text{const}$; $\beta = 0$. Due to the gravitational focusing, the cross section of encounters with massive binaries is much higher than with low mass stars. In addition, the ejection velocities from encounters with massive stars are higher. Observationally, massive stars also have a much higher binarity fraction, as well as separation distribution which is biased toward closer binaries (lower mass stars seem to have a log normal distribution of periods; Duquennoy & Mayor 1991). For all these reasons, the majority of runaway stars are ejected through interactions of massive stars with massive binaries. For simplicity, we neglect dependence of $dR(a)$ on the specific mass function of binaries in Eq. (4), and assume some fiducial effective typical mass for the stars involved in the dynamical encounter. Interestingly, our numerical simulation results suggest that this may be justified even for a range of stellar masses, however, we leave the more detailed analytic study of this dependence for further investigation.

Eq. (4) can be directly transformed to the production rate of high velocity stars per unit volume and velocity interval dv_{esc} :

$$\frac{dR(v_{\text{esc}})}{dv_{\text{esc}}} \approx 4G M_B v_{\text{esc}}^{-(\alpha+1)/\alpha} n(a) n_B n_* v_c \sigma(a) \propto v_{\text{esc}}^{-\left(\frac{2+\alpha-\beta}{\alpha}\right)}. \quad (6)$$

Making use of Eqs. (1) and (3) we can find the expected velocity distribution of the ejected stars, for some appropriate choice of the binaries separation distribution. For an Öpik's distribution of the semi-major axis $n(a) \propto a^{-1}$ we expect the velocities of ejected stars to be distributed as $R(v_{\text{esc}}) \propto v_{\text{esc}}^{-8/3}$ ($\alpha = 3/5$; $\beta = 1$), while for $n(a) = \text{const}$. we get $R(v_{\text{esc}}) \propto v_{\text{esc}}^{-13/3}$ ($\alpha = 3/5$; $\beta = 0$). This approach can be naturally extended to any desired distribution of binary separations.

3. N-BODY SIMULATION MODELS

We have studied several different numerical models of star clusters in order to characterize the properties of runaway stars. We also make use of simplified cluster models to verify our analytic calculations of the the velocity distribution of ejected runways. Table 1 summarizes basic physical parameters of the models which were integrated by means of NBODY6 code (Aarseth 1999). In all cases, distribution of the binary semi-major axis was truncated outside the interval (0.05 AU, 50 AU); initial eccentricities were set to zero. In the first models we studied a highly simplified stellar systems in which only two masses were used rather than a continuous mass function. All binaries in these models are made of identical $10 M_{\odot}$ components and the single stars are identical $1 M_{\odot}$ stars; in addition, all stars are treated as point-masses in these models. Later we also compared these to simulations results of similar clusters with no primordial binaries, to verify that single-single encounters can only lead to ejections with $v_{\text{esc}} \lesssim 20 \text{ km s}^{-1}$. During the cluster evolution, dynamically formed binaries could eject stars at higher velocities, but the overall fraction of runaways was only a small fraction than in the case of clusters including primordial binary population.

Though in this study we focus on the simple cluster simulations, we also run simulations of somewhat more realistic clusters, in which the full ranges of Salpeter initial mass func-

tion (IMF) for the stars is considered. In the latter models, all massive ($M \geq 4 M_{\odot}$) stars reside in primordial binaries, and we set a lower limit for the primary and the secondary star to $4 M_{\odot}$ and $1 M_{\odot}$, respectively. We use pairing algorithm which prefers similar masses of the two components which is in accord with observations. Furthermore, binary stars in real clusters may physically collide. Hence, we enable the possibility of stellar collisions for these models in order to increase their realism; stars are merged if they pass to each other at a distance smaller than the sum of their radii.

The process under the consideration, i.e. acceleration of stars to velocities $> 60 \text{ km s}^{-1}$ is quite rare. Therefore, we have integrated several hundreds of different realizations (N_{run}) of each model in order to obtain statistically relevant results.

4. RESULTS

4.1. Velocity distribution

Figure 1 shows the velocity distribution of escaping stars (found at least 5 pc away from the host cluster at the end of the simulations). The figure shows the velocity distribution compared with the predicted distribution at the high velocity regime (when taking the overall normalization to be a free parameter). Although the analytic derivation does not account for the mass function, we find that the velocity distribution of ejected stars in models 009 and 014 are also consistent with simple analytic formulation, and the slope is determined mainly by the distribution of the semi-major axis of the binaries (see fig. 1). The velocity distribution at the lower velocity regime $v_{\text{esc}} \approx 20 - 150 \text{ km s}^{-1}$ is qualitatively different, and appears to be independent of the distribution of the binary separation. Comparison with a model where no binaries exist show that all the bona-fide runaway stars arise from the existence of binaries in the clusters. Although not the focus of this paper it is interesting to note in passing that stars with velocities in the intermediate velocity range $20 - 150 \text{ km s}^{-1}$ can not be explained by single-single encounters alone; however, they also do not follow the simple analytic approach described before, but rather appear to follow a shallower distribution which is independent of the binary separation distribution. This may be consistent with the recent results of Fujii & Portegies Zwart (2011) who studied runways from massive clusters in this range of velocities. These may arise from the dynamical interactions with a small number or even single very massive binaries in the cluster (bullies), which dominate the ejection rate and are later on ejected themselves from the clusters. The properties of runways from such interactions are independent of the overall binary population characteristics. Our findings in Fig. 4 showing ejection of very massive runaway binaries is consistent with this picture. Note, however, that models 016 and 017 did not include massive binaries, which can play the role of 'bullies'. Unfortunately, we did not keep data on specific interactions leading to runaway ejections; we therefore can not directly confirm or refute this scenario for the low velocity regime. We defer such simulations and analysis to future work.

4.2. Binarity of runaway stars

The binarity of runaway stars is an important signature of the dynamical ejection scenario. Previous studies of dynamically ejected runaway stars suggested their binary fraction to be low relative to the binary fraction of their parent stars

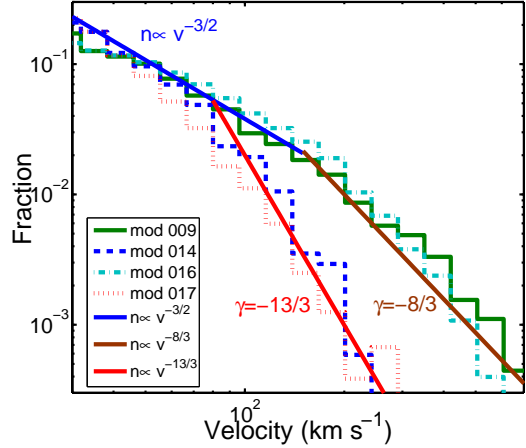


FIG. 1.— The velocity distribution of runaway stars ejected from the simulated clusters with velocities larger than 20 km s^{-1} . The runaways velocity distribution for cluster of different binary separation distribution are shown; Dash-dotted and solid stair lines are for a log-constant SMA distribution (models 009 and 016, respectively) and dash and dotted lines are for uniform SMA distribution (models 014 and 017, respectively). See Table 1 for initial conditions of all simulated clusters. The right segment of the straight lines (solid brown and red) show the toy-model predictions for the runaway velocity distributions, normalized to fit simulated data. Left segment of the straight lines (solid blue) show power law distributions with $n \propto v^{-1.5}$. Note that although the predicted slopes provide the correct trends for the models, the best fitting (not shown) power law slopes for the same high velocity regimes, $v > 150 \text{ km s}^{-1}$, are -2.5 and -2.9 for models 009 and 016, respectively (compared with the predicted $\gamma = -2.7$); and for the other models, with velocity regime $v > 80 \text{ km s}^{-1}$, we get -3.4 and -3.3 , for models 014 and 017, respectively (compared with the predicted $\gamma = -4.3$)

in the cluster (Leonard & Duncan 1990). We find a similar trend; Fig. 2 shows the velocity distribution of single and binary runaways in models 009 and 014 of our simulations (for which a realistic binary period distribution was used), and the binary fraction of runaways as a function of their velocity. The simulations results are consistent with theoretical arguments; in a binary single encounter the binary receives a smaller fraction of the kinetic energy, $M_*/(M_B + M_*)$ (Portegies Zwart et al. 2010), it is therefore typically ejected at considerably lower velocities. Note that encounters where the single star is much more massive than the binary components likely lead to an exchange of the massive components with one of the lower mass binary components, therefore even such encounters would eventually lead to the binary being the most massive component in the encounter, further contributing to its low ejection velocity, compared to the ejection of single stars. Binary-binary encounters may eject a binary to higher velocities, however, these complex encounters may easily disrupt one of the binaries and/or form higher multiplicity systems. A hard binary can be ejected similar to the ejection of single star by a softer binary, however its typical ejection velocity would be comparable to the orbital velocity of the wide binary, again producing a bias toward low velocity ejections. The overall binary fraction of runaways decreases significantly with higher ejection velocities; and effectively no binary was ejected at velocities higher than $\sim 150 (300) \text{ km s}^{-1}$ in the 009 (016) models (compare with the ejection velocities of single stars). Hyper-runaway binaries are therefore not likely to be produced through the DES (see also Perets 2009b; Brown et al. 2010 for discussions on this issue).

model	N_{run}	r_h (pc)	T_{max} (Myr)	S	M_c (M_\odot)	IMF	$n(a)$	N_{bin}	M_p (M_\odot)	M_s (M_\odot)
009	200	0.2	2.7	0.25	5000	Salpeter	a^{-1}	≈ 73	> 4	> 1
014	500	0.2	4.4	0.25	5000	Salpeter	const.	≈ 73	> 4	> 1
016	200	0.4	35.5	0	10000	$200 \times 10 M_\odot + 8000 M_\odot$	a^{-1}	100	10	10
017	200	0.4	35.5	0	10000	$200 \times 10 M_\odot + 8000 M_\odot$	const.	100	10	10

TABLE 1

Parameters of the models: initial half-mass radius r_h , index of the initial mass segregation S (see Šubr et al. 2008), total mass of the cluster M_c , distribution of the binary semi-major axis $n(a)$, initial number of binaries f_{bin} and mass of the primary M_p and secondary M_s star. Salpeter initial mass function has power-law profile $\propto M_*^{-2.35}$ within the interval $(0.2 M_\odot, 80 M_\odot)$. In the models 009 and 014, physical collisions of stars are allowed (i.e. the mass function is not constant). Initially, the binaries have semi-major axes in the range $(0.05 \text{ AU}, 50 \text{ AU})$ and zero eccentricities. Profiles of initially mass segregated models cannot be expressed analytically but, in general, their density increases towards the center.

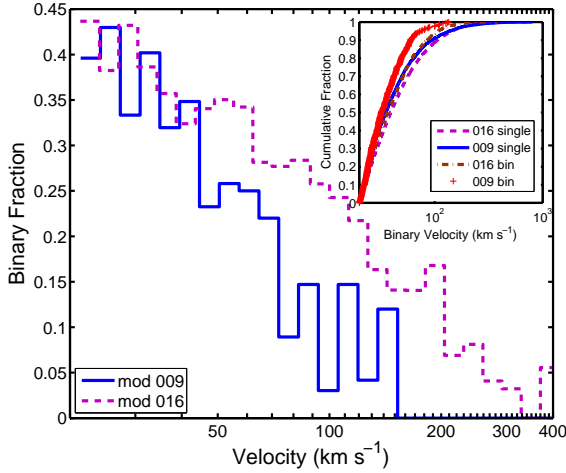


FIG. 2.— The binary properties of runaway stars. The binary fraction of runaway stars, as a function of the ejection velocity in models 009 and 016. Inset: The cumulative velocity distribution of runaway binary stars.

4.3. The mass function and mass-velocity relation for runaway stars

In Fig. 3 we show the runaway fraction of stars. As can be seen, OB runaways are relatively more abundant than lower mass stars, with the O-star runaways fraction 2-3 times larger than that of the B-stars, consistent with observations (see Stone 1991 and refs. therein).

The total fraction of runaways we find are comparable to, but systematically lower ($\sim 1/2$) than those reported by Stone (1991); this may result from the limited time of the simulation; the lifetime of typical O-stars could be 2-3 times longer than the simulation time (which is comparable to the lifetime of the most massive stars in our simulations). Obviously, many other simplified assumptions we use affect our theoretical results, and may contribute to the difference.

In Fig. 4 we present the mass-velocity distribution of the ejected stars. We see again the trend of more massive stars having higher runaway fraction (as reflected by the large fraction of massive runaways compared with their fraction in the IMF); we note that even the most massive stars are ejected as runaways. We also find that the velocity distribution of more massive runaways tends towards higher velocities than the lower mass stars, i.e. the fraction of more massive stars increases with ejection velocity. In fact, we find that ~ 20 (10) % of the runaway O-stars with $v > 20$ (100) km s^{-1} are more massive than $40 M_\odot$, and ~ 5 (3) % of the O-stars are with $v > 20$ (100) km s^{-1} are more massive than $80 M_\odot$ (consistent with finding of very massive runaway stars; e.g. Hoogerwerf et al. 2001). The latter are runaway merger products of two or more less massive stars, since the adopted IMF of the clusters prior mass cut-off was $80 M_\odot$.

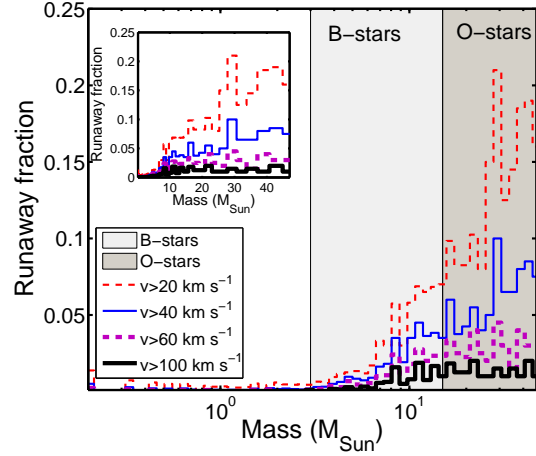


FIG. 3.— The fraction of runaways vs. mass with given (lower limit) velocities for model 009. All stars below $4 M_\odot$ are initially single stars, and their runaway fraction might be non-realistic. For OB stars $m > 4 M_\odot$ the runaway fraction increases with mass. This trend is consistent with the observed runaway fractions of O stars to be 3 – 6 times larger than the runaway B-stars fraction (see Stone (1991) and refs. therein). Note that even the most massive stars are ejected as runaways; some of which are merger products, with masses extending beyond the initial mass distribution (not shown).

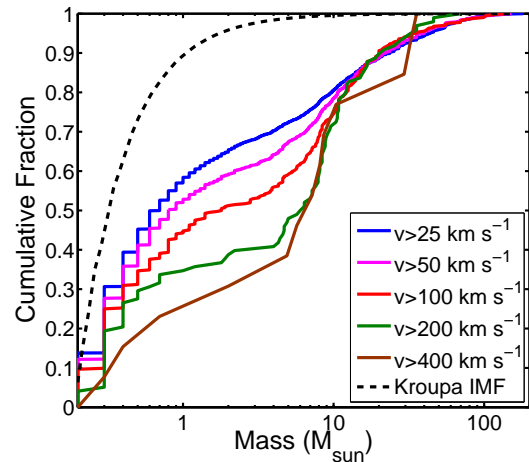


FIG. 4.— The mass function of runaway stars in mod 009 as a function of lower limit velocity. The distribution tends to be bi-modal, with runaways in the range $1 - 4 M_\odot$ typically being least represented in the population (compare with the shown IMF of all stars in the initial simulated clusters).

4.4. Hyper-runaways and hyper-velocity stars

As can be seen for both the two-mass models and the continuous mass ones, the high velocity tail of the distribution follows a steep power law. The ejection or the fastest runaways requires the close encounters with binaries, the rate of which are dominated by the most dense clusters (which

are also the most massive ones, typically). Therefore, in order to provide a basic estimate of the ejection of the fastest runaways we consider here only the most massive clusters in the Galaxy. The average number of hyper-runaways ejected with $v_{\text{esc}} > 300$ (> 450) km s^{-1} , in our most realistic cluster, model 009, is ~ 0.2 (0.02) stars per cluster. Currently, $N_c \sim 10 - 20$ young ($< t_c = 10$ Myrs) massive clusters ($M > 10^4 M_\odot$) with cores comparable to our simulated clusters exist in the Galaxy (Murray & Rahman 2010). We therefore expect the ejection rate of hyper-runaways to be $\sim 0.2 \times N_c \times t_c^{-1} = 0.2 - 0.4 \text{ Myr}^{-1}$. For B-stars (of masses $\sim 3 - 10 M_\odot$ such as observed among the hyper-velocity stars in the Galactic halo), the rate is ~ 2.5 times lower. Over 100 Myrs (comparable to the propagation time for the observed HVSs in the Galactic halo), we therefore expect to have of order 10-20 hyper-runaways in the galaxy, but only one or two such stars with $v_{\text{esc}} > 400$. Currently ~ 20 HVSs ($v_{\text{esc}} > 400$; though this is generally a good definition, note that a more accurate definition also depends on distance from the Galaxy, see Perets et al. 2009) have been observed in the Galactic halo, from which a total of ~ 100 B-stars (of $3 - 4 M_\odot$) are inferred to exist in the Galaxy (Brown et al. 2006a, 2009; Brown 2011, and references therein), and a few hundred lower velocity HVSs (so called bound HVSs; $275 < v_{\text{esc}} < 400$ Brown et al. 2007), may exist in the Galaxy (Perets et al. 2009). Comparing the predicted and observed numbers of HVSs, hyper-runaways from this scenario may contribute at most $1 - 2\%$ of the HVSs population and are unlikely to have produced any of the currently *observed* HVSs in the Galactic halo (or at most one); though they may contribute a small fraction of the observed bound HVSs.

5. SUMMARY

In this paper we explored the dynamical ejection of runaway stars from the cores of massive stellar clusters. We presented a simple analytical toy model to explain the velocity

distribution of the fastest runaway stars. We then used extensive N-body simulations of simplified clusters composed of only two type of stars with masses 1 and $10 M_\odot$ to characterize the velocity distribution of runaway binaries; later we also simulated clusters with realistic continuous Salpeter IMF. We found the trends in velocity distribution to depend on the properties of binaries in the cluster and be generally consistent with the analytical toy models of multi-interactions with multiple binaries at the high velocity regime $v \gtrsim 80 \text{ km s}^{-1}$ (or $v \gtrsim 150 \text{ km s}^{-1}$; depending on the model). At the lower velocity regime, ejection velocities are less dependent or possibly even independent of the binary properties, suggesting a different channel for runaway ejections dominate this regime (e.g. Fujii & Portegies Zwart 2011).

We characterized the velocity distribution of runaways from the continuous IMF clusters, and discussed their mass function and binarity. We find that the runaway fraction of stars increases with mass, consistent with observations; and that very massive stars formed through collisions in the cluster could be ejected as runaways. The binarity of runaways stars decrease with increasing velocity, and is generally lower than the binary fraction of their birth cluster. In particular, we find the maximal velocity of binary runaways is limited to $< 200 \text{ km s}^{-1}$. We also find the mass function of runaways to be velocity dependent. Although runaways are much more frequent amongst the massive stellar population $> 4 M_\odot$, we find that a large population of low mass runaways should also exist. The ejection rate of hyper-runaways, with velocities $> 300 \text{ km s}^{-1}$ appear to be too low to explain a significant fraction of the observed HVSs in the Galactic halo, and could at most explain a small fraction of the observed bound HVSs.

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